Hydraulic and Civil Engineering Technology VII
M. Yang et al. (Eds.)

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doi:10.3233/ATDE220970

Study on the Influence of Ship Speed and Ship Weight on Ship-Bridge Collision Force

Keke PENG [a,1] and Qiming PAN [a]
[a] *School of Transportation and Civil Engineering & Architecture, Foshan University, Foshan, Guangdong, 528225 China*

Abstract. Based on finite element method, combined with numerical simulation, the calculation algorithm of ship-bridge collision effect is given. The general formula of impact force is derived at first. Then, in order to obtain the functional relationships between ship speed, ship weight and collision force, a four continuous rigid frame highway channel bridge is taken as an instance of real bridge , the influence of ship weight and ship speed on the impact force during the ship bridge collision was analyzed. By using ANSYS / LS-DYNA software, the three-dimensional simulation dynamic finite element model of ship bridge collision was established. Numerical simulation calculations were carried out for the crest value of impact force of the ship bridge under the above two factors. Subsequently, statistical fitting analysis was carried out on calculation results. Based on numerical simulation results, the linear function relationships between the crest value of impact force and the secondary root of the ship weight and the ship speed are obtained, which provides a basis for the crest value of impact force in bridge anti-collision design.

Keywords. Ship-Bridge collision, ship speed, ship weight, peak impact force, dynamic finite element model

1. Introduction

The mechanical research of ship-bridge collision involves many factors such as ship type, ship speed, and bridge structure. In terms of theoretical analysis, Minorsky [1] specially studied several ship collision accidents for the purpose of the design and safety of nuclear-powered warships. A linear relationship was discovered between the deformation of the steel volume and the absorbed impact energy, which is called the Minorsky curve. Fu et al. [2] developed a damage finite element model of a bridge span to identify and illustrate the significant difference between bridge health state and state the damage through studying the frequency response of vibration data. Yanchen et al. [3] proposes a simplified analytical mode for ship-bridge collision events, which is able to predict the time-history of impact loading on bridges with sufficient precision when the basic structural frequency of the bridge pier is under 3 Hz. Comparing the test results with the finite element calculations, Sitong [4] obtained the mathematical expression of the vehicle bridge impact spectrum by fitting the period displacement

[1] Keke Peng, Corresponding author, School of Transportation and Civil Engineering & Architecture, Foshan University, Foshan, Guangdong, 528225 China; E-mail: Pengkeke@fosu.edu.cn.

amplification factor curve with a mathematical method. In terms of numerical simulation of finite element software, Chaoyi et al. [5] simulated the whole process of the train passing the bridge when the ship impact force acted on the piers and analyzed the dynamic response of the bridge and vehicle by LS-DYNA. Yuanying [6] used ANSYS/LS-DYNA to simulate the collision between a 3000 Deadweight ton (DWT) cargo ship and a pier. The dynamical response of the structure was analyzed and the general law of impact force, ship weight, and impact speed was obtained. Juan et al. [7] established a refined LS-DYNA finite element model of vehicle bridge collision and pointed out that the peak impact force increases with the development of vehicle weight under the condition of constant vehicle speed. Anil et al. [8] researched the response of RC column under the impact loading in free falling body. An ABAQUS finite element model was established and the mechanical properties of RC columns under low-speed impact were consequently determined. Gholipour et al. [9] used LS-DYNA to calculate the effect of axial force on the dynamical response of Reinforced Concrete (RC) columns subjected to horizontal impact force. ANSYS/LS-DYNA is used by Keke [10] considered the dynamic factors of the channel using ANSYS/LS-DYNA dynamic finite element model and proposed using the improved AASHTO method to study the impact force and ship collision risk probability.

According to the above research status, the study of ship bridge collision based on finite element numerical simulation has been well carried out in recent years. Some scholars use ABAQUS software (Anil et al. [8]) while most of them use ANSYS / LS-DYNA software (Junhu et al. [11], Yuanying [6], Gholipour et al. [9], Jian et al. [12] and Keke [10]). Obtained calculations results from ANSYS / LS-DYNA are consistent with the test results indicating that the collision mechanics process can be accurately simulated by the software. Therefore, ANSYS software modeling and LS-DYNA for post-processing analysis are used in this study. The process of pier collision under different speeds and loads has been studied by several researchers (Miao et al. [13], Yuanying [6], Juan et al [7]., Jian et al. [12]) However, the research on the above multi-factor coupling effects of ship bridge collision has not been fully carried out, most ship collision analysis still follows the equivalent static empirical formula of AASHTO code (AASHTO [14] 2009) or Eurocode (Eurocode1 [15] 2002). These formulas are mainly obtained by experience, which does not reveal the relationship between the peak impact force as a function of ship speed and ship weight. The evaluation index of ship impact force is relatively single, and the description of ship impact force is not comprehensive enough. China's general code for the design of highway bridges and culverts (JTJ D60-2015 [16]) points out that special research should be carried out on the impact effect of ships, and the results can be used as the determining action value after approval and other procedures (Ministry of Transport of the People’s Republic of China [16] 2015). Therefore, it is essential to quantify the ship impact force to address the shortcomings of the above research.

2. General Formula for Calculating Impact Force

According to the principle of conservation of energy, the general expression of impact force F is deduced as the following formula derivation.

The speed of the ship is supposed as v , the mass is m, the stiffness is K_1, and the pier stiffness is supposed as K_2 . After the collision of the ship and bridge, the displacement of the pier is Δ, and the deformation of the ship is δ, the formula of kinetic energy is as Equation (1),

$$E = \frac{1}{2}mv^2 = \int_0^{\delta} K_1 x dx + \int_0^{\Delta} (K_2 + x) dx = \frac{1}{2}K_1\delta^2 + \frac{1}{2}K_2\Delta^2 \tag{1}$$

According to the geometric compatibility conditions of impact force F, stiffness K_1, K_2, displacement Δ, and deformation δ, the following equation is obtained,

$$F = K_1\delta = K_2\Delta \tag{2}$$

According to Equation (2):

$$\delta = \frac{F}{K_1}、\ \Delta = \frac{F}{K_2} \tag{3}$$

Substituting Equation (3) into Equation (1), the following equation is obtained,

$$\frac{1}{2}mv^2 = \frac{1}{2}K_1(\frac{\mathrm{F}}{\mathrm{K_1}})^2 + \frac{1}{2}K_2(\frac{\mathrm{F}}{\mathrm{K_2}})^2 = \frac{1}{2}F^2(\frac{1}{K_1} + \frac{1}{K_2}) \tag{4}$$

According to Equation (4), the functional relationship between the ship speed, mass, structural stiffness and impact force can be obtained, as shown in Equation (5),

$$F = v\sqrt{m(K_1 + K_2)} \tag{5}$$

3. Finite Element Model

3.1. Engineering Background

The bridge crosses the mainstream of the Xijiang River in Guangdong province. The width of the water surface at the bridge location is about 1100m, the clear height of navigation is 22m, the clear width is 18m, and the two holes are navigable in one direction. The elevation of the bridge type is depicted in figure 1. The superstructure of the sample bridge is 112 + 2 × 200 + 112m prestressed concrete continuous rigid frame with a C60 concrete box girder. The width of a single span bridge is 16.38m, the height of the beam is 4.20-11.60m, the section is variable, and the piers are double limb thin-walled piers.

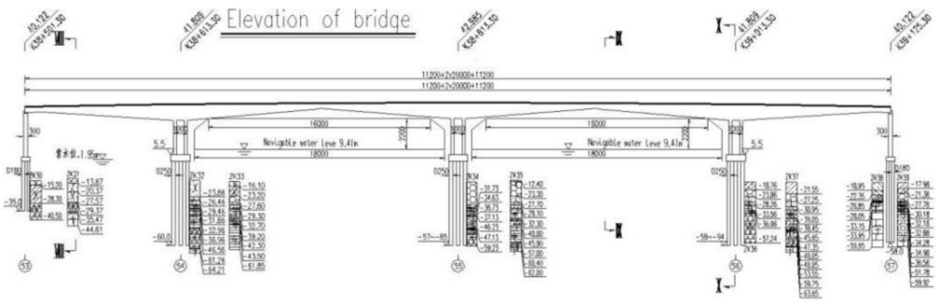

Figure 1. Elevation layout of the sample bridge.

3.2. Modeling Ideas

HJC constitutive relation model is used for concrete, elastic-plastic constitutive relation model is used for steel bar, Mass166 element is used for the superstructure, solid 64 elements is used for Pier and cap, link160 element is used for steel bar, combin165 spring element is used for pier top, and shell163 element is used for bow and hull. The superstructure and pier were assumed rigid structures and the top of the pier was simulated with spring, while the bottom of the pier was fixed with constraint. The above boundary conditions are shown in figure 2. The meanings of K1, K2, m, and v in figure 2 are the same as those in Eq. (1). H1 is the impact height and H2 is the distance from the pier top to the center of gravity of the superstructure. The three-dimensional finite element model for the pier of the example bridge is displayed in figure 3.

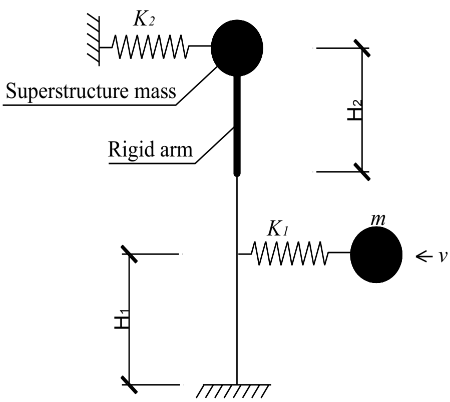

Figure 2. Structural mechanics diagram.

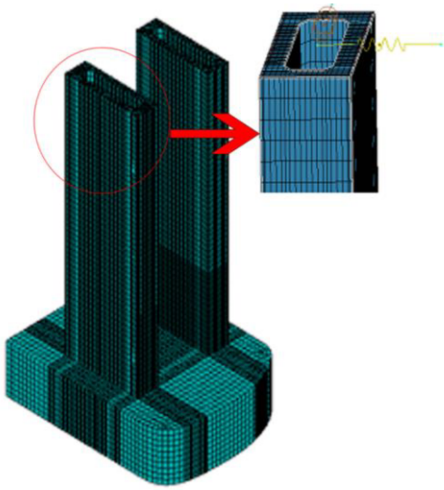

Figure 3. Three dimensional model of pier.

The above three-dimensional simulation model is established by ANSYS APDL command flow, and the K files of LS-DYNA are used to solve the ship-bridge collision model. The working case combinations are described in section "Multi-parametric study for peak impact force".

4. Multi-parametric Study for Peak Value of Impact Force

4.1. Influence of Ship Weight on Peak Impact Force

In order to explore the influence of ship weight on the crest value of impact force, the ship weight m is changed with other variables unchanged, and the functional relation between ship weight and impact force is analyzed. When the impact height is 8.45m and the ship speed is 2m/s, taking 500t as the equal difference, eight ship collision models from 500t to 4000t are established. A total of 32 ship collision models with 8 different tonnages and 4 ship speeds of 2m/s, 4m/s, 6m/s, and 8m/s were analyzed. The fitting curves are demonstrated in figure 4.

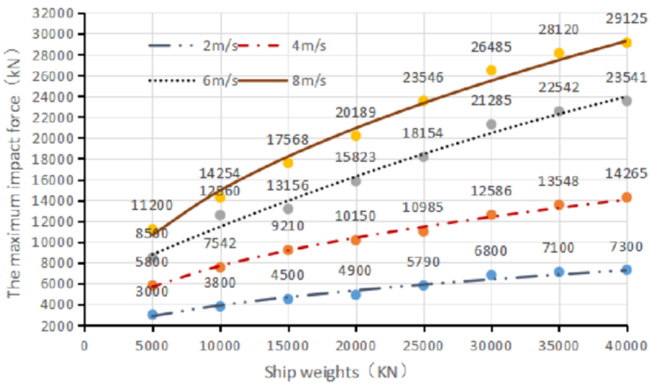

Figure 4. Fitting curve of the relationship between ship weight and the crest value of impact force.

According to the fitting results, the functional relation between the ship weight and the crest value of impact force appears a power function, which can be expressed as Equation (6).

$$F = A\sqrt{M} \tag{6}$$

In which, F is the crest value of impact force, M is the ship weight. A is a real constant which obtained through mathematical statistics, it changes with the ship speed. The greater the ship speed, the greater the coefficient A. However, for a fixed ship speed, A is unchanged.

4.2. Influence of Ship Speed on Peak Impact Force

In order to explore the influence of a ship speed on the peak impact force, the relationship between the ship speed and impact force is analyzed by changing the ship speed with other variables unchanged. When the impact height is 8.45m and the ship load is 500t, 32 ship impact models with 8 different deadweight tonnages and ship speed of 2m/s, 4m/s, 6m/s, and 8m/s are analyzed. The fitted curves are shown in figure 5.

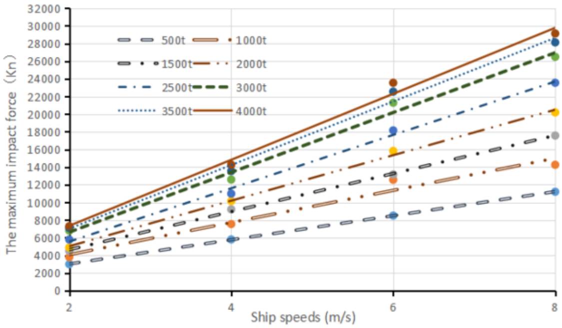

Figure 5. Fitting curve of the relationship between ship speed and the crest value of impact force.

According to the fitting results, there is a linear functional relation between them. the crest value of impact force and impact velocity can be expressed by Equation (7).

$$F = Bv \tag{7}$$

In which, F is the crest value of impact force, v is the ship speed. B is a real constant which obtained through mathematical statistics, it changes with the ship weight, The greater the ship weight, the greater the coefficient B. But for a fixed ship weight, v is unchanged.

5. Conclusions

Based on the general formula of impact force derived from the conservation of energy, a comparative analysis of the current code formulas was carried out. Using a continuous rigid frame highway channel bridge as an instance, the dynamic finite element model of ship bridge collision is established by using ANSYS / LS-DYNA software, and a large number of numerical simulation calculations are carried out for the peak impact force of ship-bridge under the influence of ship weights and ship speed. The results are analyzed by statistical fitting. The influences of ship weight and ship speed on the peak impact force are analyzed. According to the analysis results, the following can be concluded:

(1)The general formula of ship collision force deduced based on energy conservation, European code [15], AASHTO code [14] and Chinese Railway code [17] all show that the collision force has a linear relationship with the secondary root of ship speed and ship weight.

(2) According to the fitting results, the ship weight has a power function relationship with the crest value of impact force; There is a linear functional relation between ship impact velocity and the crest value of impact force. This conclusion is consistent with the general formula of ship impact force.

(3) The calculation method of ship bridge collision effect combined with finite element method and numerical simulation is given, which provides a theoretical basis and effective method for the research of ship bridge collision effect in bridge anti-collision design.

This method is a supplement to the current highway code [16] in China, and can dynamically and comprehensively describe the possible impact load on the highway channel bridge, and can be extended to similar highway channel bridges as well.

Acknowledgments

The authors would like to acknowledge the Characteristic Innovation Project of Guangdong Universities (Project number: 2020KTSCX128), the Natural Science Foundation of China (Project number: 51608119), and the Free Exploration Fund for Graduate of Foshan University ((Project number: 2021ZYTS01), which collectively funded the research work presented in this paper.

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